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Non-mechanical behaviors of soft clay in two-dimensional electro-osmotic consolidation

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Abstract: To investigate the soil behaviors in a direct current field on both spatial and temporal scales, a 1: 5 scale model test was conducted in laboratory to simulate the two-dimensional (2D) electro-osmotic consolidation of soft clay foundation. Volume of drainage, intensity, voltage, water content and pH value of water collected in the cathodes were monitored. The pH values of soil and the mass of anodes were measured before and after the test. The test results indicate that the unsaturated state, resultant from fissures induced by the differences in water contents, is favorable to dynamic compaction of soil during electro-osmotic drainage. The results also demonstrate that water content, degree of saturation and electric potential distributions can be used to deduce the electro-osmotic drainage process. Water content of soil decreases first near electrodes, while keeps nearly constant in the center of the model. The area with constant water content is larger than half of the sample surface. Moving anodes towards cathodes by about one third of the electrode spacing is effective to improve the treatment effect after electro-osmosis stops due to the large resistance. Moreover, it is observed that during electro-osmosis, the corrosion rate of anodes becomes smaller, while the variation in pH values of soil near anodes becomes larger.

Key words: electro-osmotic consolidation; soft clay; degree of saturation; voltage; pH value of soil; anode corrosion

1 Introduction

It is usually time-consuming or even useless to improve soft clay foundation using mechanical consolidation methods, including vacuum preloading or only preloading. But it should be noted that land reclamation is continuing at a rate of 230–240 km^2 per year in Chinese coastal cities (Dong et al., 2010), and huge amount of sludge was dredged from rivers and lakes every year (Ji et al., 2010). Electro-osmosis is regarded as one of the promising methods developed to overcome the shortages of conventional methods. The electro-osmotic drainage rate is independent of soil particle size, and the electro-osmosis improved ground would not fail due to the lack of bearing capacity of soil, because the increase in effective stress is just caused by the decrease in pore water pressure.

Electro-osmotic method was introduced and used successfully as a dewatering tool in Germany railway by Cassagrande in 1939. Since then, electro-osmosis has been employed in many projects in North America, Europe and China. Bjerrum et al. (1967) employed electro-osmosis technique to stabilize an excavation in very soft Norwegian quick clay near Oslo, resulting in almost fourfold increase in average undrained shear strength. Lo et al. (1991) demonstrated that in a field test by an appropriate design of electrodes and polarity reversal, pumping at the cathode could be canceled. The increase in soil shear strength was demonstrated as the expansion of the effective strength envelopes and increase in the pre-consolidation pressure (Lo and Ho, 1991). Burnotte et al. (2004) showed that the effect of electro-osmotic consolidation of soft clay could be improved by minimizing power loss at electrodes through chemical treatment in a laboratory study and a large field demonstration test. Hu (2004)

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reported a highway subgrade reinforced effectively by electro-osmosis.

In spite of several successful field applications mentioned above, this technique is not widely used in practice, and has only been used in the situations where other conventional methods are not applicable. The reason may be attributed to the limited understanding of the mechanism of electro-osmosis, which has led to high power consumption, ineffectiveness and improperly designed operating systems.

The behaviors of soft clay during electro-osmotic treatment have attracted much attention from researchers. It has been generally observed that after soil improvement, water content has a significant decrease near anode but little change near cathode. In addition, acid condition is formed around anode and alkaline condition is formed around cathode. These phenomena usually occur in the line connecting anode and cathode after consolidation. Considering that the 2D rectangular array of electrodes is the most common style in practice, it is necessary to study the changes in soil properties with time in the whole electrodes plane.

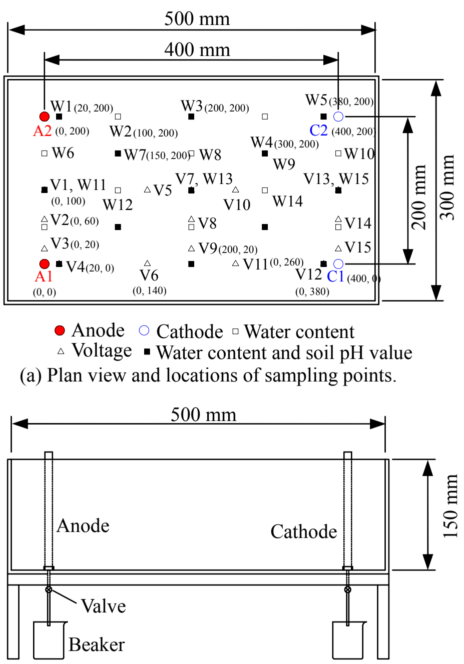
This paper presents a laboratory test to reveal the spatio-temporal distribution of water content, degree of saturation, voltage and pH values of soil in a 2D electro-osmotic consolidation of soft clay, and their variations with time and location are monitored and the mass of anodes is also measured at the end of the test.

2 2D electro-osmotic consolidation test for soft clay

2.1 Testing device

In the development of an electro-osmosis cell, the following factors are considered: (1) reproduction of electro-osmotic drainage and current between vertical tubular electrodes as those in field; (2) the cell dimensions should have the same scale with the corresponding parts in a typical field installation, considering electrode diameter and spacing; (3) the cell is large enough to sample soil for the study of geotechnical properties after an electro-osmotic test; (4) the cell is insulated from leakage and electric conduction; (5) the drainage condition can be adjusted to satisfy the boundary conditions; (6) the applied electric field is approximately two-dimensional; and (7) the voltage distribution, electric current, and water flow in the soil sample can be measured at any time during testing without power interruption.

A schematic diagram of the cell developed for electro-osmotic tests is shown in Fig. 1. The electro-osmotic cell is a rectangular tank made of 5 mm-thick Plexiglas plates, which could accommodate a soil sample with dimensions of 500 mm×300 mm×150 mm (length×width×height). Four fixing holes of 10 mm in inner diameter and 13 mm in outer diameter are installed in the base plate of the electro-osmotic cell. Each fixing hole could act as both a base to locate the electrode and a drainage passage connected with a valve at the end of the cell.



(a) Plan view and locations of sampling points.

(b) Profile.

Fig. 1 Schematic diagram of the electro-osmotic cell.

The electrodes are made of perforated nickel plating stainless tube of 10 mm in diameter and 150 mm in length. During the electro-osmotic tests, cathodes are wrapped with gauze to avoid clay particles flowing from the holes in cathodes with expelled water.

A voltage is applied by using a direct current (DC) power supply, with a maximum capacity of 3 A and 120 V. The power supply has the ability to display the current of soil sample in real time. The voltage distribution across the sample is measured by several voltage probes, which are made of stainless wires and are inserted about 120 mm deep into the sample. Locations of voltage probes are shown in Fig. 1(a) by mark “V”, and mark “W” stands for the locations of water content sampling point.

2.2 Physicochemical properties of soil

Xixi sedimentary soil mixed with tap water was used in the tests to simulate a hydraulic filling in the land reclamation. The sedimentary soil was sampled from the bottom of an excavation in Zijingang Campus of Zhejiang University, Hangzhou, China. The physicochemical properties of the intact soil are summarized in Table 1. The sedimentary soil is characterized as clay with 8% sand, 38% silt and 54% clay fraction. The soil is normally consolidated with a very low undrained shear strength and an unconfined compressive strength of 6.8 kPa. The sensitivity, the ratio of undrained shear strengths before and after complete disturbance, of the clay is 2.1. The liquid and plastic limits of the natural sedimentary soil are 52% and 22%, respectively. The dominant clayey minerals are illite and chlorite with quartz as the major non-clay minerals. The water content of remolded soil before electro-osmosis is about 67%. The electrical conductivity of the soil after mixing is 0.135 S/m. The pH value of the pore water in remolded soil is 6.0.

Table 1 Physicochemical properties of the intact clay.

Water content (%)	Specific gravity	Degree of saturation (%)	Liquid limit (%)	Plastic limit (%)	pH value
55.5	2.73	99.7	52	22	6.5

2.3 Testing schemes

Two tests, T1 and T2, with almost identical initial conditions were conducted. They have the same layout of 400 mm in spacing between electrodes of opposite polarity (L), and 200 mm in spacing between electrodes with the same polarity (b), which is corresponding to a practical array of 2 m×1 m at a scale of 1: 5. Similarly, the electrodes of 10 mm in diameter were used to simulate the mild steel pipes with a diameter of 50 mm used in practice. The test duration of T2 was set as half of T1's so that the final behaviors of clay in T2 are the same as those of the first half of T1.

During preparation of the two tests, the intact soil was made firstly to powder by drying, grinding and screening. Then, the powder was mixed with tap water (pH value of 6.0) till the water content reached about 67%. The mixture was left for 24 hours to ensure that water in the whole soil sample was evenly distributed. It was carefully placed in the electro-osmotic cell up to a height of 150 mm to minimize the voids and entrapped air. The inner surface of the cell was lubricated with Vaseline in order to reduce the friction between soil and Plexiglas. Electrodes were installed in the fixing holes before filling. After applying voltage prior to connecting electric circuit and adjusting valves, the probes were inserted into the soil, as shown in Fig. 1(a). Drainage was only allowed at the cathodes. Water expelled from the cathodes was collected by beakers below to measure its volume.

For the two tests, the applied voltage was maintained constant all the time and voltage gradients were kept at 1.25 V/cm. The electric current and voltage were monitored. Power was shut off on schedule, i.e. 96 and 48 hours for tests T1 and T2, respectively. The water content and pH value of soil were measured before and after each test. Volume and pH value of the expelled water were measured at intervals during testing. The pH value was measured with test paper which has a precision of ±0.1. Degree of saturation near the electrodes was measured after treatment. The locations of electrodes, sampling points of water content and voltage probes were illustrated in Fig. 1(a). The coordinates were also provided based on that the location of anode A1 was regarded as the origin point. Shear strength was not included in the index monitored, but this didn't obscure the comprehension of test results, because there is a quantitative relationship between strength and water content for the remolded soils (Micic et al., 2001).

3 Results and discussions

3.1 Water content and degree of saturation

As shown in Fig. 2, there are fewer differences in the current and volume of drainage between T1 and T2. It means that the attempt to make the final condition in T2, simulating the one in the half of T1, is successful. The current gradually decreases from the maximum value of 0.76 A at the beginning to the minimum value of 0.15 A at the end of test. Inversely, the volume of electro-osmotic drainage increases with time. Both drainage rate and current intensity decrease during testing.

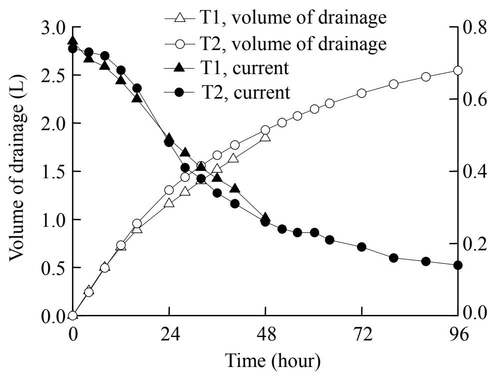
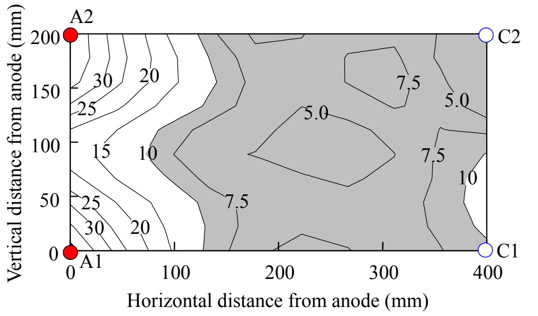
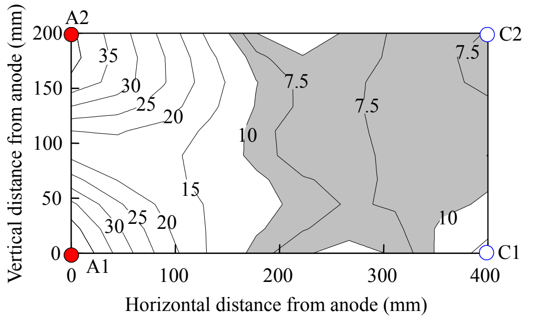


Fig. 2 Volume of drainage and current during consolidation.

The final distributions of decreases in water content of T1 and T2 are shown in Fig. 3. After 48 hours, the water content of soil decreases radially outwards from anodes by 30%–35%. About two thirds of sample surface area in the vicinity of cathodes has almost the same water content reduction of 5%–10%, and herein it is called the nearly unchanged area, as grey area shown in Fig. 3(a). Unlike the results described in the literature, the largest water content is in the center of rectangular model with electrodes in the corners. After 96 hours, only a water content reduction of 2.5% is achieved in the nearly unchanged area, while that of the soil around anodes decreases to 35%. Moreover, at the same distance, the water content of soil in the midline (linking water content sampling points W11 and W15) is lower than that in the beeline (connecting anode and its corresponding cathode such as A1 and C1), especially near anodes.



(a) After 48 hours.



(b) After 96 hours.

Fig. 3 Distribution of decrease in water content (unit: %).

The process of electro-osmotic drainage can be deduced from the water content contours. Generally, the direction of water flow induced by a direct current field is from anode to cathode in the clay which has a negative surface charge. Soil around anodes is dried rapidly while there is little change in the water content of soil around cathodes. Some water is arrested in the region around cathodes with a horizontal distance of about $L/3$. It may due to too large voltage gradient or too short treating time. The arrested water can be expelled by further treatment and the water content will be reduced. Water dissipation does not stop until the current is not able to drive pore water. Because of the increasing resistance, drainage rate reduces gradually. Based on the distribution of final water content, the electro-osmotic drainage may continue by moving anodes towards the cathodes for a horizontal distance of about $L/3$.

Significant change in the sample volume is not observed during the test, while the volume of water collected at cathodes is much large, indicating that the treated clay is unsaturated. It is confirmed by the result of saturation test (Fig. 4). At the beginning of electro-osmosis, the clay is completely saturated; after 48 hours, the degree of saturation of soil near anodes is about 80% and the clay near cathodes is still saturated. After 96 hours, the degree of saturation of soil around electrodes reduces to approximately 55%. Fig. 5 implies that the unsaturation of soil is caused by the large cracks near anode.

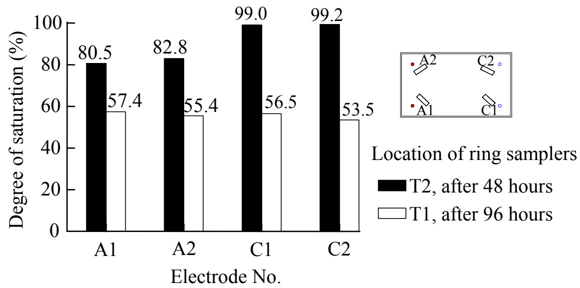


Fig. 4 Degrees of saturation of soil after consolidation.

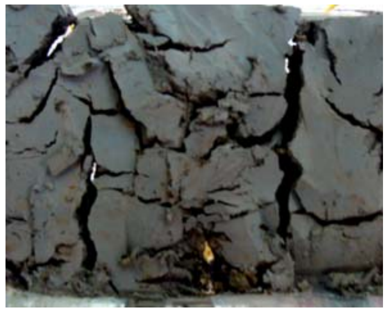
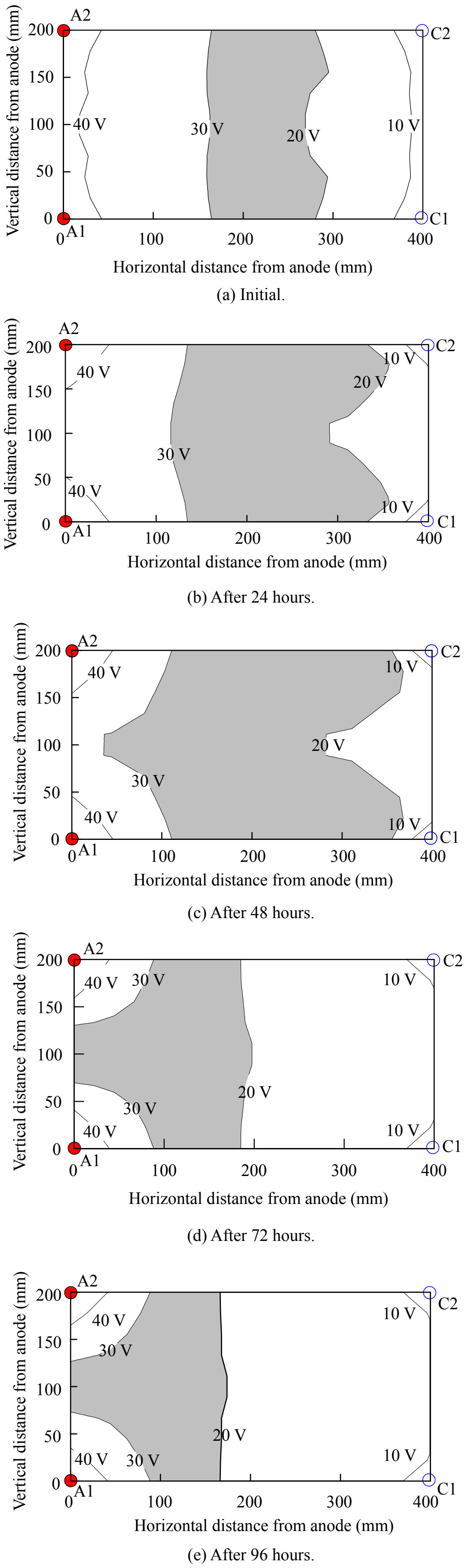


Fig. 5 Profile of soil near anode after electro-osmosis.

It seems that the increment in effective stress is not large enough to compact the pores in soil, making it possible that large cracks would be caused by uneven reduction in water content. External load can be used to compact soil and restrain propagation of cracks, thus to improve the treatment effect. The combination of electro-osmosis and low-energy dynamic compaction in Chinese costal practices can enhance the efficiency of soil consolidation.

3.2 Voltage

Fig. 6 shows the spatio-temporal distributions of voltage. Just after power-on, the equipotential contours of different voltages are nearly parallel and equal-spaced, due to the initial homogeneity of soil.



(a) Initial.

(b) After 24 hours.

(c) After 48 hours.

(d) After 72 hours.

(e) After 96 hours.

Fig. 6 Voltage contour maps among electrodes at different times.

The contour maps change in the following 96 hours. The 40 V equipotential lines are nearly fixed around the anodes after 24 hours, while the 10 V equipotential lines around cathodes at a closer distance. Within 72 hours, the 30 V equipotential lines move towards anodes all the time. The locations of 20 V equipotential lines are more complex compared to the other three potentials, moving towards cathode in the former 48 hours and towards anodes in the latter 48 hours. Voltages contour map could be better understood associated with water content distributions (Fig. 3). The reasons, to explain the 10 and 40 V equipotential lines in a short period of time after power-on, are attributed to the quick desiccation of soil near anodes and little change in water content of the soil near cathodes. Compared with soil near cathodes, soil near anodes has a larger water content reduction, namely a larger resistance. The 30 V lines move towards anodes while the voltage consumed by soil near anodes increases. The movement of 20 V lines is related to the nearly unchanged water content area aforementioned. The existence of the nearly unchanged water content area makes the spacing between 20 and 30 V lines be larger than $L/2$ in the former 48 hours and equal to $L/2$ in the latter 48 hours. The region with low equipotentials has more uniform distribution of water content.

The variation in voltages with time is displayed by another mode of profiles between anode and cathode, with normalized coordinate and data obtained by voltage probes V4, V6, V11 and V12 (Fig. 7). Voltage of probe V4 near cathode C1 decreases with time, while that of probe V12 near anode A1 keeps constant. An evident decrease is observed between probes V4 and C1. The decrease reflects that much larger resistance exists at the soil-cathode contact interface, as described by Mohamedelhassan and Shang (2001, 2002). There is also abnormal resistance at the soil-anode contact interface though it is not as obvious as that at the soil-cathode contact interface.

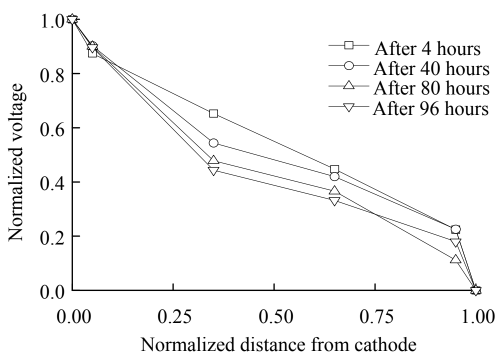


Fig. 7 Voltage profiles at different times.

The efficiency factor β is defined to quantify the contact resistance between soil and electrodes:

$$\beta = \frac{V_0 - (\Delta V_a + \Delta V_c)}{V_0} \tag{1}$$

where V_0 is the supply voltage, ΔV_a is the voltage at the soil-anode interface, and ΔV_c is the voltage at the soil-cathode interface.

Fig. 8 shows the calculation results of Eq. (1) based on the data obtained by voltage probes V3, V4, V12 and V15. Efficiency factors seem to be constant in the consolidation process and have an average value of 0.79, which is in the range of empirical values suggested by Cassagrande (1983) after studying the collected case histories of electro-osmotic treatment.

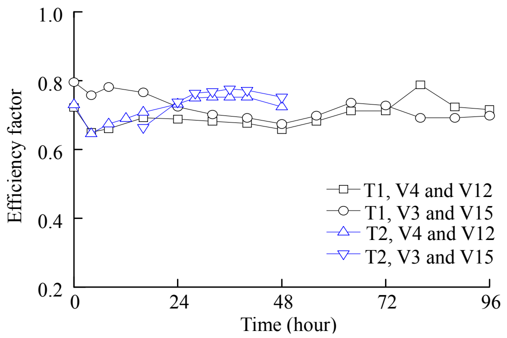


Fig. 8 Efficiency factors for the two tests.

3.3 Soil pH value and anode corrosion

Electrochemical reactions associated with DC electro-osmosis have been identified and discussed extensively. Electrolysis occurs due to the oxidation of water to hydrogen ion (H^+) and oxygen gas at the anode and the reduction of water to hydroxyl ion (OH^-) and hydrogen gas at the cathode:

$$2H_2O - 4e^- \rightarrow O^2 \uparrow + 4H^+ \quad \text{(Anode)} \tag{2}$$

$$2H_2O + 2e^- \rightarrow H^2 \uparrow + 2OH^- \quad \text{(Cathode)} \tag{3}$$

As a result, acidic and alkaline environments are generated around the anode and cathode, respectively. H^+ moves towards the cathode, generating an acid front; while OH^- migrates as a base front towards the anode. If electrodes are made of mild steel, corrosion occurs at the anode:

$$Fe - 2e^- \rightarrow Fe^{2+} \tag{4}$$

Further oxidation changes the ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}). Fe^{3+} and other cations are driven to the cathode by the electric field and form hydroxides with OH^-. Except for several hydroxides, including KOH and NaOH, most hydroxides are insoluble at pH value >5 (Shang, 1997):

$$M_i^{n+} + OH^- \rightarrow M_i(OH)_n \downarrow \tag{5}$$

where M_i^{n+} is the dissolved cation species i in solution.

Fig. 9 shows the corroded anode A1 and the cathodes C1 and C2 with wrapped gauze after test. White insoluble substance can be observed on the gauze. The acidic and alkaline environments are caused by the changes in the pH values of expelled water and soil. The pH value of water collected in the cathodes rises to 12.0 in 4 hours after power-on and remains almost constant thereafter. The variations in pH value of soil along the length of samples after treatment are shown in Fig. 10. The samples in the midline have a gentler pH value change compared to that in the beeline. The increase in treating time leads to a decrease in pH value of soil, which implies that hydrogen cations produced near the anodes are transported continually to the cathode.

(a) Anode A1. (b) Cathodes C1 and C2.

Fig. 9 Anode and cathodes after test.

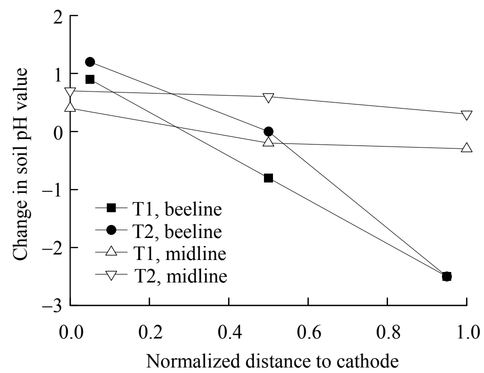


Fig. 10 Variations in pH value of soil.

To investigate the degree of corrosion, the mass of anodes is measured before and after treatment. The degree of anode corrosion, S (%), can be estimated by

$$S = \frac{M_0 - M_f}{M_0} \times 100\% \tag{6}$$

where M_0 and M_f are the mass of the electrode before and after treatment, respectively.

The degrees of anode corrosion for the two tests are presented in Fig. 11, showing that the degree of anode

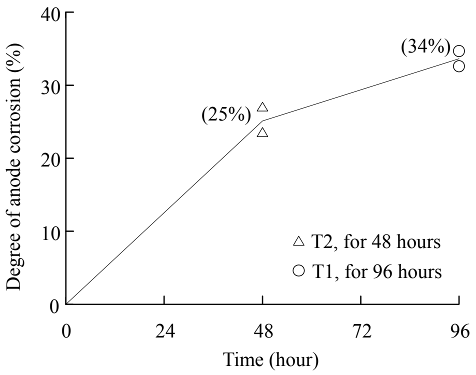


Fig. 11 Degree of anode corrosion with time.

corrosion is associated with elapsed time. A more slow corrosion rate is observed in the second half of T1. The current curves as shown in Fig. 2 can be used to interpret the result. The current intensities at the end of T1 and T2 are 0.14 and 0.27 A, respectively. Faraday's law gives a directly proportional relationship between the loss of electrode mass due to corrosion and current intensity.

4 Conclusions

More and more constructions in the soft foundation make it necessary to improve foundation effectively and economically. As a promising method, detailed study of the electro-osmotic consolidation method is needed. A laboratory test using self-developed device is conducted to determine the spatio-temporal distributions of water content, degree of saturation, voltage and pH value of soil. From the test results, the following conclusions can be drawn:

(1) In the direct current field, clay changes from completely saturated state to finally unsaturated state. The spreading direction of unsaturation was the same as the direction of water flow. The cracks in the soil are caused by uneven distribution of water content. The combination of electro-osmosis with external load or dynamic compaction is proven to be feasible.

(2) The distribution of water content is also dependent on the electro-osmosis treating time. An area with little reduction in water content is observed, and it covers two thirds of sample surface around cathodes. It may be caused by the difference in the water flow into cathodes and from cathodes. After 48 hours' treatment, the area with the little reduction in water content is reduced evidently. The effective method to decrease water content of clay after a long electro-osmosis is that moving anodes towards cathodes.

(3) The process of electro-osmotic consolidation can be deduced based on the distribution of electric potential. Soil near anodes is dried fast and equipotential lines approach towards anodes. Approximately 21% supply voltage is lost in the soil-electrode contact.

(4) Electrolysis is accompanied with electro-osmosis. The acidic and alkaline environments are caused by the changes in the pH values of expelled water and soil. The degree of anode corrosion decreasing with elapsed time is defined. The pH value of soil also decreases with elapsed time, which implies that H^+ produced near the anode is transported continually to the cathode.

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